HADRONIC JOURNAL 49, 27 - 64 (2026)
DOI 10.29083/HJ.49.01.2026/SC27

NEW PERSPECTIVES AS REGARDS THE BLACK HOLE INFORMATION AND FIREWALL PARADOXES IN A THREE-DIMENSIONAL DYNAMICAL QUANTUM VACUUM

Davide Fiscaletti
SpaceLife Institute – Via Roncaglia 35 - 61047
San Lorenzo in Campo (PU), Italy
spacelife.institute@gmail.com

Received January 13, 2026
Revised January 26, 2026

Abstract

New perspectives to address the black hole information and firewall paradoxes are introduced in the model of a three-dimensional dynamical quantum vacuum defined by a variable energy density and by dissipative processes at a generalized Compton wavelength that provides a unified treatment of macroscopic regime of black holes and quantum regime of elementary particles in terms of sub-Planckian black holes of the variable energy density. The information paradox is treated without invoking a firewall. Finally, it is shown how the dissipative features of the vacuum allow a new re-reading of the connection between the information contained in the effective interior of the black hole and the modes outside the apparent horizon, avoiding the paradoxes present in current theories.

Key words: three-dimensional dynamical quantum vacuum, generalized Compton wavelength, black holes, dissipative features of the vacuum, apparent horizon, entanglement effect of the apparent horizon.

Copyright © 2026 by Hadronic Press, Inc., Palm Harbor, FL 34684, USA

1. Introduction

In the exploration of the properties of black holes, Stephen Hawking originally suggested that the information encoded by things that fall into a black hole is lost [1], while the laws of quantum physics imply that information cannot be destroyed and gauge/gravity duality demonstrates that this information is carried away by the Hawking radiation. Despite the progresses obtained by current theories, today there is yet the problem whether the Hawking radiation carries information about matter that falls in the black hole and whether the quantum information encoded by the matter that collapsed to originate the black hole is destroyed and lost forever. The conflicts between quantum mechanics and general relativity as regards the treatment of black holes can be summarized in the two famous information paradox and firewall paradox.

In order to face the information paradox, in some famous works Susskind et. al. [2-4] suggested the so-called black hole complementarity, namely the idea that the information is both emitted at the horizon and passes through the horizon in such a way that a freely falling observer crossing the horizon would detect nothing out of the ordinary, while an external fixed observer sees this information emitted by complicated dynamics at or very near the horizon, detecting a significant feature known as the "stretched horizon". In this picture, quantum mechanics is saved at the cost of locality because the location of information in the Hilbert space cannot be found. According to the Susskind model, an observer who falls into a black hole after extracting information from the Hawking radiation would not be able to detect the same information inside the black hole before reaching the spacelike singularity, considering that the information absorbed by the black hole can be recreated after the so-called Page time [5]. In other successive works, Hayden and Preskill [6] suggested that, if information is thrown into a black hole after the Page time, it is possible to evade the duplication of information because that it can still be reconstructed after the so-called scrambling time, which is usually less than the Page time.

An alternative way to handle the black hole information paradox could be the consideration of creation of particle–antiparticle pairs on the event horizon and of the escape of a particle when black hole captures its antimatter partner. However, this path does not allow a satisfactory solution, because of the quantum entanglement property named monogamy (i.e. the fact that double entanglement is not permitted to particles simultaneously). In order to avoid a multiple entanglement among particles, antiparticles and Hawking radiation,

Almheiri, Marolf, Polchinski and Sully (AMPS) proposed the idea of a breaking of the particle-antiparticle entanglement at the horizon. In the AMPS model, the release of energy corresponding with this broken entanglement generates the formation of a "firewall" at the black hole boundary, which avoids any act of penetrating the interior of the black hole horizon [7-9], by burning up any infalling observer. AMPS argued that the three assumptions of black hole complementarity, i.e.:

1. Hawking radiation is pure (in the sense that is kept in pure states);
2. Effective field theory is valid outside a stretched horizon;
3. infalling observers encounter nothing unusual as they cross the horizon (i.e. any low-energy dynamics these observers can probe near their worldlines is well-described by familiar Lorentz-invariant effective field theory)

cannot be simultaneously self-consistent. Assuming then that effective field theory is valid and that Hawking radiation is pure, the AMPS work showed that the paradox regarding the simultaneous considerations of these three assumptions of black hole complementarity can be avoided only if photons, emitted with the Hawking radiation, which is traced backward in its path, and modes behind the horizon are not entangled (because a possible entanglement would provoke violations of semiclassical physics at macroscopic distances from the horizon). A crucial point of the AMPS model lies in the fact that equivalence principle, Hawking radiation and quantum entanglement cannot be considered together all, i.e. that one assumption must be removed in order to make the theory self-consistent. In particular, if the entanglement is eliminated, it means that Hawking radiation will no longer be linked to particles that have passed the event horizon, and we cannot predict the information which fell into the horizon through Hawking radiation: in this way, a loss of information and consequently a violation of the conservation of information occur. On the basis of the AMPS work, the information is saved if one considers the formation of a firewall built of a set of high-energy particles near the horizon of the original black hole and that stores the information contained inside the black hole.

However, the implications of the firewall are someway problematic. In the light of Hawking's results [10], the action of the horizon as a "firewall" proposed by AMPS violates the equivalence principle predicted by general relativity and breaks the CPT invariance of quantum gravity. As an alternative proposal, Hawking suggested that, in the formation of a black hole, no real event horizon is formed behind which information is lost and somehow the gravitational

collapse generates only apparent horizons and does not continue beyond them. In this picture, therefore, there would be no black holes, in the sense of regimes from which light cannot escape to infinity and black holes should be only defined as metastable bound states of the gravitational field. Recently, Vaz [11] developed the Hawking idea of the apparent horizon as final result of the gravitational collapse by considering a quantum gravitational model of dust collapse, which implies that a nonstop collapse towards a singularity emerges only if one considers a combination of two independent solutions of the Wheeler-DeWitt equation in terms of shell wave functions:

$$\psi_i = \psi_i^{(1)} + A_i \psi_i^{(2)} \quad (1)$$

where $\psi_i^{(1)}$ represents dust shells condensing to the apparent horizon on both sides of it and $\psi_i^{(2)}$ represents dust shells that move away from the apparent horizon on either side of it where the exterior, outgoing wave is suppressed by the Boltzmann factor at the Hawking temperature for the shell. In this picture, the AMPS firewall paradox is avoided if A_i tends to zero, thus making $\psi_i^{(1)}$ the complete description of the quantum collapse till the apparent horizon.

In this paper, we want to throw new light as regards the explanation of the information loss paradox and firewall paradox of black holes, which go beyond the results obtained by Vaz, on the basis of some interesting insights that can be found in the current literature on the subject.

Before all, as regards the effects associated with matter approaching a black hole horizon within the framework of quantum physics, some recent developments have been performed which do not require additional bizarre assumptions about spacetime structure or modifications to quantum mechanics. In particular, the problem of an information paradox has recently received a new re-reading on the basis of the observation that, close to the event horizon of a black hole, there is a modification of the homotopy class of particle trajectories, and this topological property causes a local alteration of quantum statistics in any collective system of indistinguishable identical particles that pass internally from the rim of the photon sphere (at a distance of $1.5r_S$ from a central singularity of a Schwarzschild black hole, where r_S is the event horizon radius) [12]. A release of energy is associated with this quantum collective statistics transition, compatibly with unitary evolution in quantum mechanics. This release of energy implies the generation of some kind of firewall located at the photon sphere rim instead of a hypothetical one on the event horizon.

According to the author of the present paper, the idea of the formation of a firewall positioned at the photon sphere rim seems compatible with the idea of the gravitational collapse of the black hole till an apparent horizon (as the one invoked by Vaz in [11]), where the photon sphere expands from the photon rim to the apparent horizon. On the basis of the results obtained in [13], an important feature of the photon sphere rim lies in the fact that, if a particle was passing the photon sphere rim inward, an inevitable falling occurs toward the apparent horizon: in the region $r_S < r < 1.5r_S$, the trajectories are spirals directed towards the horizon for particles that overcome the photon sphere rim. As a consequence of the fact that the particles devoid of quantum statistics create a pure quantum state of individual particles which cannot interchange their positions, the entropy or information connected to quantum statistics are not carried by the matter that next crosses the apparent horizon, and this constraint modifies premises for the information paradox [14, 15], in that the role of some kind of firewall is taken by the radiation burst released during the passing by the falling matter of the photon sphere rim relatively distantly from the apparent horizon.

Moreover, according to the author, another important line of research that is worth to be followed is represented by the so-called "Generalized Uncertainty Principle", which extends the usual Heisenberg's Uncertainty Principle in the quantum-gravity regime [16] and has the merit to introduce new scenarios in the exploration of the thermodynamics of black holes as well as the duality between elementary particles and black holes [17-24]. There are several facts that evidence the potential of the generalized uncertainty principle in providing new keys of understanding of the issues connected to black holes. For example, it has been demonstrated that the parameter appearing in the generalized uncertainty principle is proportional to the number of fields [25] and that the generalized uncertainty principle may provide a natural picture in order to reconcile unitarity as perceived by an exterior observer who remains coherent with [macroscopic] superpositions of black hole states, and the infalling observer who does not experience anything special at the horizon, fully in agreement with quantum field theory on curved spacetime in its regime of validity [26]. Moreover, despite the implications of generalized uncertainty principle for information loss problem have not yet been well-studied, the generalized uncertainty principle can throw new light also on the black hole information paradox by suggesting that there is not a loss of information when a black hole evaporates, but instead is encoded and retrieved through quantum effects near the black hole. In

particular, in [27], two distinct generalized uncertainty principle models have been considered, the first which embeds minimal length, the second which embeds both minimal length and maximal momentum where, through rigorous calculation of emission correlations and remnant entropy, it was found that the total entropy remains conserved, ensuring unitary evolution without information loss, thus providing a reconciliation between black hole thermodynamics and quantum mechanics principles and critical insights into resolving the information paradox through quantum gravity frameworks.

Now, in this paper, taking account of these recent results, we want to propose new alternative paths in order to fuel the debate about the treatment of the black hole information and firewall paradoxes. In this regard, we consider a model of a three-dimensional dynamical quantum vacuum (3D DQV), proposed by the author in recent papers [28-36], which postulates the existence of an underlying variable quantum vacuum energy density and, by starting from a peculiar specific form of generalized uncertainty relations, leads to define a universal scale that provides a unified treatment of macroscopic regime of black holes and quantum regime of elementary particles.

The paper is organized as follows. In section 2, we review the fundamental features of the background space invoked by our model of the 3D DQV. In section 3 we explore our interpretation of time as a sequential numerical order of material change ultimately emerging from the dissipative features of the 3D DQV. In section 4, we show how the dissipative features of the vacuum allow us to avoid the concept of firewall at the boundary of a black hole, leading directly to new perspectives of solution of the paradoxes connected to the three assumptions of black hole complementarity. In section 5 we explore how the information loss in black holes can be treated in our model. In section 6 we analyse the relation between interior evolution and exterior evolution of a black hole. Finally, in section 7 we recap the main results of the paper.

2. The geometrodynamic picture of the three-dimensional dynamical quantum vacuum and the sub-Planckian black holes of the variable energy density

In the model of the 3D DQV, the geometric features of the background are associated with the following peculiar specific form of generalized uncertainty relations, which are valid at the Planck scale:

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta l_p^2 \frac{\Delta \rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (2).$$

In equation (2) $\Delta\rho_{qvE}$ is the variable energy density of the vacuum corresponding to the appearance of a material particle of mass m in a volume V, defined as

$$\Delta\rho_{qvE} \equiv \rho_{pE} - \rho_{qvE} = \frac{mc^2}{V} \quad (3),$$

where

$$\rho_{pE} = \frac{M_{Pl}c^2}{l_p^3} \quad (4)$$

is Planck's energy density (M_{Pl} being Planck's mass, c the light speed and l_p Planck's length) intended as the ground state of the 3D DQV, β is a fluctuating dimensionless parameter which expresses the fact that here one deals with quantum vacuum fluctuations, associated with virtual particles, that fix the minimal length scale only on average, $\hbar$ is Planck's reduced constant and the term $\frac{\hbar}{2}\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}$ measures the degree of violations of the Heisenberg uncertainty relations at scales that approach the Planck scale. The generalized uncertainty relations (14) is directly derived by starting from the operators

$$\hat{P}_k^2 = \left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right)\hat{p}_k \quad (5)$$

$$\hat{X}_j = \hat{x}_j \ + O(\beta^2) \quad (6)$$

where $\hat{x}_j$ and $\hat{p}_k$ satisfy the ordinary Heisenberg uncertainty relations, which obey the commutator

$$[\hat{X}, \hat{P}] = i\hbar\left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (7).$$

By starting from the generalized uncertainty relations (2), one obtains a suggestive unification of the quantum regime of elementary particles and the macroscopic regime of black holes in terms of a generalized Compton wavelength which provides a unified expression for the Compton wavelength and Schwarzschild radius, given by relation

$$R'_C = R'_S = \sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} \quad (8).$$

On the basis of the generalized Compton wavelength (8), one recovers the standard value of the Schwarzschild radius for $\frac{\Delta\rho_{qvE}V}{c^2} \gg M_{Pl}$ where M_{Pl} is the Planck mass, and the standard value of the Compton wavelength associated to an elementary particle for $\frac{\Delta\rho_{qvE}V}{c^2} \ll M_{Pl}$. The physical meaning of equation (8) is that the origin of elementary particles of the quantum world and of material objects and black holes of macroscopic regime is represented by elementary objects of the

Planck scale, namely sub-Planckian black holes with a size of order of their Compton wavelength, i.e. opportune aggregates of one or more virtual particles of the 3D DQV corresponding to the geometrodynamic properties of the variable quantum vacuum energy density.

In the model of the 3D DQV, the generalized Compton wavelength can be considered as the universal scale where quantum regime and general relativity can be unified. The activity of the sub-Planckian black holes of the underlying variable energy density at the scale (8), generates a deformation of the geometrical properties of the background expressed by a quantum-modified Schwarzschild metric which has the following form

$$ds^2 = F(r)c^2dt^2 - F(r)^{-1}dr^2 - r^2d\Omega^2 \quad (9)$$

where

$$F(r) = 1 - \frac{\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2}}{r} + \varepsilon \frac{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2}{4r^2} \quad (10)$$

and $d\Omega^2 = d\theta^2 + sin^2\theta d\phi^2$ is the metric on the 3-sphere and ε is a dimensionless deformation parameter of the metric that, in analogy to the treatment made in [37], satisfies the constraint $|\varepsilon| \leq 1$. The standard Schwarzschild metric of general relativity can be considered as a special case of the more general quantum-modified metric (10), in the sense that the quantum-modified metric (10) determines corrections in the values of the global deflection angle of light, the total precession of the orbit of a planet, the time dilation and the gravitational red-shift with respect to the corresponding formulations predicted by standard general relativity, leading to general formulas which allow the standard corresponding general relativistic relations to be recovered under appropriate limits [38]. Moreover, the impact of the deformation parameter ε in the Hawking temperature of black holes has been explored, showing reduced quantum evaporation rates for positive values of ε and enhanced Hawking radiation for negative values of ε [39].

The generalized Compton wavelength (8) plays an important role also as regards cosmology. In fact, in our theory each micro-region of the universe here can be described by a wave-function Ψ (which is a function of the scale factor a and of the scalar fields φ associated with the quantum vacuum energy density fluctuations as well as the polarization of the vacuum), that satisfies a peculiar form of Wheeler-DeWitt (WDW) equation, intended as an equation of background, a real "equation of everything" where all the possibilities of the physical world are written in timeless form:

$$\ddot{\Psi}+\frac{k\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}\Delta\rho_{qvE}}{\alpha c^2\sqrt{\alpha}}\Psi+\omega^2(a)\Psi=0 \quad (11).$$

In equation (11), $\dot{\Psi}=\frac{\partial\Psi}{\partial a}$, α is the fine-structure constant, ω is the mode frequency linked with the scale factor and, finally, k is an adimensional parameter corresponding to the size of the condensate of virtual sub-particles of the 3D DQV, namely represents a sort of effective parameter of density of the virtual particles of the medium [40]. By invoking the third quantization formalism, the wave function Ψ of the universe satisfying WDW equation (11) is promoted to the role of operator, which can be expressed as

$$\hat{\Psi}_{\pm}=$$

$$\frac{V\Delta\rho_{qvE}}{\sqrt{2\pi}\hbar l_p^2}\int d\rho\left(e^{\pm i\frac{V\Delta\rho_{qvE}}{\hbar l_p^2}\varphi}\Psi_{\Delta\rho_{qvE}}(a)\hat{b}_{\Delta\rho_{qvE}}+e^{\mp i\frac{V\Delta\rho_{qvE}}{\hbar l_p^2}\varphi}\Psi^*_{\Delta\rho_{qvE}}(a)\hat{b}^{\dagger}_{\Delta\rho_{qvE}}\right)$$

(12)

where $\hat{b}_{\Delta\rho_{qvE}}$ and $\hat{b}^{\dagger}_{\Delta\rho_{qvE}}$ are the annihilation and creation operators which annihilate and create respectively micro-universes, associated with corresponding changes of the quantum vacuum energy density, and satisfy the "quantum Boltzmann statistics" that consists of a q deformation of the commutation relations of the oscillators, given by the following relation

$$\hat{b}_k\hat{b}_l^{\dagger}-q\hat{b}_l^{\dagger}\hat{b}_k=\delta_{kl} \quad (13)$$

where the cases $q=\pm1$ correspond to bosons and fermions. Here, the quantum operators $\hat{b}_{\Delta\rho_{qvE}}$ and $\hat{b}^{\dagger}_{\Delta\rho_{qvE}}$ are embedded in the mathematical formalism in relation to space-time in the sense that their properties are intrinsically connected to the symmetries of space-time and the way micro-universes (that can give origin to bosons or fermions) behave under transformations in the background.

The generalized Compton wavelength defines a granular structure of the 3D DQV background in the sense that one deals here with elementary cells that contain the information

$$I=\frac{A}{l_p^2} \quad (14)$$

where

$$A=k\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right] \quad (15)$$

is the area of the cell. The information (14) of the elementary cells of the 3D DQV is the fundamental element that gives rise to the appearance of a particle. In particular, the wave function (12) of a micro-universe satisfying the generalized WDW equation (11) gives

origin to the manifestation of a corresponding particle characterized by the chronon scale if the information (14) satisfies relation $I^3 l_p \approx 10^{-13} cm$, namely

$$\frac{k^3}{l_p^5}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^3 \approx 10^{-13} cm \quad (16).$$

On the basis of equation (16), an interesting aspect of the interpretation of elementary particles in the model of the 3D DQV ruled by the generalized Compton wavelength lies in the possibility of choosing opportunely the parameter k that defines the size of the condensate of the virtual sub-particles of the medium in order to obtain the appearance of the desired particle of the Standard Model with its usual properties. As a consequence, here the chronon scale of ordinary Standard Model particles can be interpreted as the emergence scale of processes of collective organization of opportune condensates of the virtual sub-particles of the 3D DQV which take place at the generalized Compton wavelength.

3. Time and dissipative features of the vacuum

In the model of the 3D DQV, the variable quantum vacuum energy density ultimately corresponding to the foam of the virtual particles of the vacuum give origin to elementary objects, namely sub-Planckian black holes, with a size of order of their generalized Compton wavelength, which can be considered as the common matrix that can give origin to elementary particles or black holes. In this picture, an ultimate quantum nature characterizes all black holes, and each subatomic particle, at the deepest level, derives from something which has similar properties of a black hole. Moreover, by following [41, 42], we consider that sub-Planckian black holes of the variable quantum vacuum energy density can be described by a cyclic intrinsic Compton periodicity, intended as the fundamental connecting element between the particle aspect and the black hole aspect of these elementary objects. In particular, here we assume that the intrinsic Compton periodicity of the sub-Planckian black holes of the variable energy density is generated, at a fundamental level, by the dissipative features of the vacuum at the generalized Compton wavelength, expressed by an opportune dispersion relation of the form

$$\omega^2 = c^2k^2 - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2}k^4 \quad (17)$$

where the wave number k is assimilated just to the inverse of the generalized Compton wavelength (8), yielding

$$\omega^2 = \frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2 V^2 \left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]^2} \quad (18) \quad [43].$$

The dissipative features of the 3D DQV described by the dispersion relation (18) imply that time/clock is described by states that are ruled by a non-linear Schrödinger equation, a peculiar version of the Gross–Pitaevskij equation of the form

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\nabla^2\psi + \frac{a^2}{2\pi}\left(\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2 V^2 \left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]^2}}\right) m|\psi|^2\psi + U\psi \quad (19).$$

In this equation, m is the mass of each sub-planckian black hole of the physical vacuum, U is the potential energy relating to the single virtual particle and ν is a viscosity coefficient having the dimensions $\frac{length^2}{time}$ which can be expressed as $\nu = \frac{a^2\omega}{2\pi}$ where a is the scattering length between the virtual particles. As a consequence of the dissipative hydrodynamics described by the Gross-Pitaevskij equation (19), the time marked by the clock has the physical meaning of sequential numerical order of material change associated with the dynamics of the system into consideration, that can be associated to the inverse of the frequency defined by the dispersion relation (17), namely

$$t = \frac{1}{\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar\ c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2 V^2 \left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar\ c}\right)^2\right]^2}}} \quad (20)$$

The physical meaning of equation (20) is just that the entanglement between the evolving system and the clock generates a counter function labelled by the hands of the clock which is linked with the frequency modes of the 3D DQV, namely with the variations of the quantum vacuum energy density, that are ultimately determined by the dissipative features of the vacuum at the generalized Compton wavelength. Therefore, in summary, we can consider that the intrinsic Compton periodicity characterizing the proto-particles of the vacuum, i.e. the sub-planckian black holes of the variable quantum vacuum energy density, is ultimately associated with the dissipative features of the vacuum at the generalized Compton wavelength and is expressed by equation (20).

4. Gravitational collapse and the apparent horizon

The dissipative features of the vacuum at the generalized Compton wavelength, by determining the intrinsic periodicity (20) of the sub-planckian black holes of the variable quantum vacuum energy density, introduce new suggestive perspectives of treatment of the paradoxes connected with the physics of black holes.

The frequency modes of the 3D DQV associated with the variations of the quantum vacuum energy density at the generalized Compton wavelength lead to sub-Planckian black holes characterizing by an intrinsic periodicity which allows us to avoid the paradoxes connected with the simultaneous consideration of the three fundamental assumptions underlying black hole complementarity invoked by AMPS. In other words, the model of sub-Planckian black holes of the 3D DQV where the dissipative features at the generalized Compton wavelength lead to an intrinsic periodicity expressed by equation (20), implies that the three fundamental assumptions underlying black hole complementarity are not necessarily incompatible. This derives from the fact that, in the light of the dissipative features of the 3D DQV at the generalized Compton wavelength, the result of the gravitational collapse is represented by extremely compact quantum objects that are ruled by quantum gravity processes and that lead to the formation of an apparent horizon whose area acts as a coarse-grained entropy.

The model based on the dissipative features of the 3D DQV can go beyond the results of Vaz's quantum gravitational model of dust collapse based on the wave function (1). By replacing the standard Wheeler-DeWitt equation with the equation of background (11) whose general solutions are the wave functions (12), the gravitational collapse involving the birth of black holes can be described by means of a lattice of collapsing dust shells, namely micro-universes, determined by the elementary sub-Planckian black holes of the variable energy density, defined by the following wave functions

$$\Psi_{\pm} = \begin{cases} \frac{V\Delta\rho_{qvE}}{\sqrt{2\pi}\hbar l_p{}^2}\, e^{\hbar\sqrt{\frac{c^2}{\left(\frac{\beta hc}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{h\ c}\right)^2}\ \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2v2\left[\left(\frac{\beta hc}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{h\ c}\right)^2\right]^2}}d} \int d\rho\left(e^{\pm i\frac{V\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi_{\Delta\rho_{qvE}}(a)\hat{b}_{\Delta\rho_{qvE}}+e^{\mp i\frac{V\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi^{*}_{\Delta\rho_{qvE}}(a)\hat{b}^{\dagger}_{\Delta\rho_{qvE}}\right) \\ \frac{V\Delta\rho_{qvE}}{\sqrt{2\pi}\hbar l_p{}^2}\, e^{\hbar\sqrt{\frac{c^2}{\left(\frac{\beta hc}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{h\ c}\right)^2}\ \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2v2\left[\left(\frac{\beta hc}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{h\ c}\right)^2\right]^2}}\left(d-\frac{\pi}{\hbar g_h}\right)} \int d\rho\left(e^{\pm i\frac{V\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi_{\Delta\rho_{qvE}}(a)\hat{b}_{\Delta\rho_{qvE}}+e^{\mp i\frac{V\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi^{*}_{\Delta\rho_{qvE}}(a)\hat{b}^{\dagger}_{\Delta\rho_{qvE}}\right) \end{cases} \quad (21).$$

The micro-universes described by equation (21) represent dust shells condensing to an apparent horizon, where g_h is the surface gravity at the apparent horizon and d is an opportune parameter $d = d(\Delta\rho_{qvE})$ that depends of the variable energy density corresponding to the formation of the shells. These dust shells have bound states of energy that can be determined by considering the following potential of interaction between the fluctuations of the quantum vacuum energy density and the quantum compact object

$$V(r) = -G\frac{\Delta\rho_{qvE}V m}{2Rc^2} \quad (22)$$

where m is the mass of the dark compact object associated with the spherical massive shell and R is the radius of the shell. In analogy to what happens in the hydrogen atom, on the basis of the potential of interaction (22), one obtains the following bound states of energy of the dust shells:

$$E_n = -\frac{1}{n^2}\frac{G^2 m^3 \Delta\rho_{qvE}^2 V^2}{2\hbar^2 c^4} \quad (23)$$

that lead to the following mass spectrum of the shells:

$$m_n = \frac{2}{n^2}\frac{G^2\Delta\rho_{qvE}^4 V^4}{\hbar^2 c^4} \quad (24).$$

As a consequence of the intrinsic non-locality associated with the quantum Boltzmann statistics satisfied by the creation and annihilation operators appearing in the wave functions (21), the position of the physical quantum shells generated during the gravitational collapse cannot be exactly localized but can be defined through an average radius expressed by relation

$$\langle R_n\rangle = \frac{3}{2}\frac{m_n c^2}{\Delta\rho_{qvE}V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} \quad (25).$$

The minimum value of the radius of these shells, in Planck units, can be computed as the difference between the volume of the sphere having radius $\langle R_n\rangle + \frac{1}{2}l_p$ and the volume of the sphere having radius $\langle R_n\rangle - \frac{1}{2}l_p$:

$$V_{min} = \frac{4}{3}\pi\left[\left(\langle R_n\rangle + \frac{1}{2}l_p\right)^3 - \left(\langle R_n\rangle - \frac{1}{2}l_p\right)^3\right] = \frac{4}{3}\pi\left[3\langle R_n\rangle^2 l_p + \frac{1}{4}l_p^3\right] = 4\pi\langle R_n\rangle^2 l_p + \frac{\pi}{3}l_p^3 \quad (26).$$

Therefore, taking account of the mass spectrum (24), one finds the following expression for the maximum value of the density of the shells:

$$\sigma_{max} = \frac{2G^2\Delta\rho_{qvE}^4 V^4}{n^2\hbar^2 c^4\left(4\pi\langle R_n\rangle^2 l_p + \frac{\pi}{3}l_p^3\right)} \quad (27)$$

This result is in agreement with the results obtained by Corda in [44] and, at the same time, shows how the maximum value of the density of

the shells generated during the gravitational collapse of the black hole is determined by variable energy density and, above all, taking account of relation (25), by the processes at the generalized Compton wavelength. In other words, we can say that the evolution of the collapsing dust shells described by the wave functions (21) leads to the formation of an apparent horizon if the density of the shells is characterized by a maximum density (27) that is directly fixed by the fluctuations of the variable energy density at the generalized Compton wavelength.

Moreover, the process of gravitational collapse of the dust shells can be associated to a corresponding behaviour of the entropy of the collapsing matter. In this regard, taking account the results obtained in [45], the formation of a black hole involves processes where the entropy of collapsing matter is converted into that of the vacuum and, during these processes, because of the entanglement between the vacuum and the arising Hawking radiation, which leads, as a consequence of the evaporation process, to the entanglement among the final-state Hawking quanta, the horizon is soft and no firewall develops. As a consequence, during the gravitational collapse of the dust shells that leads to the formation of an apparent horizon, we can consider that the black hole entropy is generated by the interaction between the virtual particles associated with the fluctuations of the 3D DQV and the black hole's apparent horizon, as well as by the entanglement between the virtual particles of the vacuum and the arising Hawking radiation. These processes of interaction imply, on the basis of the results obtained in [46], that the area of the apparent horizon μ acts as a sort of coarse-grained entropy:

$$S^{coarse} = \frac{Area\,[\mu]}{4G\hbar} \quad (28),$$

in a picture where the area of the apparent horizon can be interpreted statistically as the maximum boundary entropy that is compatible with the geometry of its exterior and therefore with the maximum density of the shells (27). Now, if the coarse-grained entropy of the apparent horizon is constrained by the maximum density of the shells (27), as a consequence of this fact, the area of the apparent horizon appearing in equation (28) derives from the geometry of the shells on the basis of relation

$$Area\,[\mu] = \frac{m_n\langle R_n\rangle}{\sigma_{max}} \quad (29)$$

namely

$$Area\,[\mu] = \frac{3}{2}\frac{m_n c^2}{\Delta\rho_{qvE}V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}\,.$$

$$\cdot\left(9\pi\frac{{m_n}^2c^4}{{\Delta\rho_{qvE}}^2V^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]{l_p}^2+\frac{\pi}{3}l_p^3\right) \quad (30).$$

By substituting equation (30) inside equation (28) and taking account of relations (25) and (24), one finds the final expression of the coarse-grained entropy (29):

$$S^{coarse}=\frac{3}{8}\frac{m_nc^2}{G\hbar\Delta\rho_{qvE}V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}\cdot$$

$$\cdot\left(9\frac{{m_n}^2c^4}{{\Delta\rho_{qvE}}^2V^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]{l_p}^2+\frac{1}{3}l_p^3\right) \quad (31).$$

On the basis of equation (31), the coarse-grained entropy associated with the apparent horizon – that in current theories is widely accepted to be proportional to the area – here is directly determined by a more fundamental behaviour of the fluctuations of the quantum vacuum energy density that generate the dissipative features of the 3D DQV at the generalized Compton wavelength. According to the author, this is an important clue of the fact that the 3D DQV plays a fundamental role as regards the issues regarding the entropy of black holes.

The model developed in this chapter provides an important lesson as regards the paradoxes connected to the firewall and the AMPS work. The lesson is the following. The physical meaning of the approach based on equations (21)-(31) is that the sub-Planckian black holes of the variable energy density give rise to collapsing dust shells that will condense to an apparent horizon that therefore can be seen as the result of the opportune elementary fluctuations of the quantum vacuum energy density and, in particular, of the dissipative features of the 3D DQV at the generalized Compton wavelength. This means that, in the physics of black holes, there will be no further collapse, namely there will be no tunnelling into the exterior and no firewall as a consequence of the processes associated with the dissipative features of the vacuum at the generalized Compton wavelength, ultimately fixed by opportune behaviours of the variable quantum vacuum energy density. The intrinsic Compton periodicity of the sub-Planckian black holes of the variable energy density – that emerges from the dissipative features of the vacuum at the generalized Compton wavelength – allows us to replace the concept of firewall and central singularity with the idea of the apparent horizon, intended as the final stage of the wave functions (21) of the collapsing dust shells characterized by the maximum density (27). As a consequence of the dissipative features of the vacuum at the generalized Compton wavelength determined by opportune fluctuations of the variable quantum vacuum energy density, the area of the apparent horizon acts as the coarse-grained entropy

(31) and this action allows us to avoid the incompatibility determined by the simultaneous consideration of equivalence principle, Hawking radiation and quantum entanglement of the AMPS argument, that here are not violated, therefore restoring the conservation of information when information reaches the apparent horizon through Hawking radiation.

In this picture, the AMPS paradox is directly avoided without further assumptions, in the sense that, as a consequence of the processes determined by the dissipative features of the vacuum at the generalized Compton wavelength regarding the formation of an apparent horizon whose area acts as a coarse-grained entropy, the three hypotheses invoked by AMPS in [7, 8] are not necessarily incompatible and thus do not lead to paradoxes connected to the black hole complementarity. Our model, by predicting the generation of an apparent horizon characterized by the coarse-grained entropy (31) that is directly fixed by the dissipative features of the 3D DQV at the generalized Compton wavelength, implies that equivalence principle, Hawking radiation and quantum entanglement are not incompatible. By demonstrating in a direct way the impossibility of the formation of a firewall, it allows us to avoid the arguments involved in the AMPS work. In this way, our proposal of solution of the firewall paradoxes allows a new re-reading of the gravitational collapse of dust shells invoked by Vaz in [44], in the sense that here it can be associated to the coarse-grained entropy (31) of the area of the forming apparent horizon that is directly fixed by the dissipative features of the 3D DQV at the generalized Compton wavelength. The background of the sub-Planckian black holes of the variable energy density whose intrinsic periodicity is determined by the dissipative features of the vacuum on the basis of equation (20) and where the gravitational collapse is described by collapsing micro-universes defined by the wave functions (21) and by the maximum density (27), allows us to naturally avoid the idea of firewall and its connected paradoxes as a consequence of the formation of an apparent horizon characterized by a coarse-grained entropy which expresses the dissipative features of the dynamical processes at the generalized Compton wavelength. Moreover, an important consequence of this model lies in the possibility to avoid the existence of singularities, in the sense that – just as a consequence of the appearance of the coarse-grained entropy (31), associated with the maximum density of the collapsing dust shells (27) – the gravitational collapse of black holes do not continue till a central singularity but would terminate at the apparent horizon. We emphasize that this result is in good agreement with Hawking's proposal [10, 6], allowing above all a novel re-reading in terms of fundamental dynamical processes at

the universal scale represented by the generalized Compton wavelength. Finally, we underline that our model of sub-Planckian black holes of the 3D DQV, by considering a coarse-grained entropy (31) associated with the dissipative features of the 3D DQV at the generalized Compton wavelength, which implies a gravitational collapse till the condensation of quantum shells to the apparent horizon, provides a suggestive alternative path with respect Penrose's model regarding infinite space-time curvature in the centre of a black hole [47] and Kerr's model regarding gravitational singularity towards the centre of black hole [48, 49].

5. Entanglement effect of the apparent horizon and consequences regarding information of the black hole

As a consequence of the dissipative features of the 3D DQV at the generalized Compton wavelength and the emerging intrinsic periodicity of the sub-Planckian black holes of the variable energy density, the physics of the black holes is ruled by a gravitational collapse of dust shells that can be interpreted as micro-universes that are defined by the wave functions (21) and have maximum density (27). The final result of these processes of gravitational collapse lies in the generation of an apparent horizon whose area acts as a coarse-grained entropy (31) directly fixed by the fluctuations of the quantum vacuum energy density associated with the dissipative features of the 3D DQV at the generalized Compton wavelength, that has an important role in providing a solution to the paradoxes connected to the firewall. Now, in this section we want to show how our model allows us to make some progresses also as regards the information problem of black holes.

In this regard a key point is that, as a consequence of the creation and annihilation operators of micro-universes that appear in the wave functions (21), that are fixed by opportune quantum vacuum energy density fluctuations and satisfy the quantum Boltzmann statistics (13), and taking account the unavoidable falling toward the apparent horizon for any particle passing the photon sphere rim inward (demonstrated in [15]), the role of the apparent horizon lies in the generation of an entanglement between the information inside the black hole and the information above the photon sphere rim and, therefore, outside the black hole, thus making the interior spacetime of the black hole as an effective description of a given exterior time. In our approach, by using the quantum-modified Schwarzschild metric (10),

the trajectories of particles in various regions near the apparent horizon, on the basis of the treatment in [13, 50], may be expressed as:

$$r = \frac{\varepsilon_0}{mc^2}\int \frac{dr}{\left(1-\frac{\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2}}{r}+\varepsilon\frac{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}{4r^2}\right)\sqrt{\left(\frac{\varepsilon_0}{mc^2}\right)^2-\left(1+\frac{\mathcal{L}^2}{m^2c^2r^2}\right)\left(1-\frac{\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2}}{r}+\varepsilon\frac{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}{4r^2}\right)}} \tag{32}$$

for the trajectory radius, and

$$\varphi = \int dr\frac{\mathcal{L}}{r^2}\left[\frac{\varepsilon_0}{c^2}-\left(m^2c^2+\frac{\mathcal{L}^2}{r^2}\right)\left(1-\frac{\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}}{r}+\varepsilon\frac{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}{4r^2}\right)\right] \tag{33}$$

for the azhimutal angle, where m, $\mathcal{L}$ and ε_0 are the particle mass, angular momentum and energy. Equations (32) and (33) imply that, in the region $(1-\varepsilon)\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} < r < 1.5(1-\varepsilon)\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}$, the trajectories regarding particles that pass the photon sphere rim appear as short spirals directed toward the apparent horizon as a consequence of the action of the dissipative features of the 3D DQV at the generalized Compton wavelength determined by opportune fluctuations of the quantum vacuum energy density.

Taking account the results obtained in [13] and the features of the trajectories expressed by equations (32) and (33), because of the quantum Boltzmann statistics that rules the collapsing dust shells determined by the dissipative features of the sub-Planckian black holes of the variable energy density at the generalized Compton wavelength, all particles entering the photon sphere from outside must fall inevitably towards the surface of the apparent horizon, that therefore emerges as source of an entanglement island between the information inside the black hole and the information outside the black hole. In other words, because of the attraction of the apparent horizon on any particle passing the photon sphere rim inward which can be associated to the gravitational collapse determined by the dissipative features of the 3D DQV at the generalized Compton wavelength, the "quantum Boltzmann statistics" that characterizes the creation and annihilation operators $\hat{b}_{\Delta\rho_{qvE}}$ and $\hat{b}^{\dagger}_{\Delta\rho_{qvE}}$ appearing in the wave function (21) of the collapsing shells implies the generation of an entanglement between the information inside the black hole and the information outside the black hole [51].

Now, the fundamental questions are the following. What is the link between the interior evolution and the exterior evolution as a consequence of the entanglement action of the surface of the apparent horizon? And, above all, what conclusions can we draw from the action of the surface of the apparent horizon as entanglement island as regards the perspectives of handling the information paradox? Our idea is the following. The result of the entanglement produced by the apparent horizon, by virtue of the generation of collapsing micro-universes associated with the wave functions (21) that imply the unavoidable falling toward the apparent horizon for any particle passing the photon sphere rim inward, lies in the formation of an effective time evolution that foliates the interior region that is different from the more fundamental, exterior time evolution, which foliates only the spacetime region outside the horizon. The surface of the apparent horizon, in the light of the dissipative features of the 3D DQV at the generalized Compton wavelength, acts as a sort of entanglement island, that indeed generates the connection between the information contained in the effective interior of the black hole and the modes outside the apparent horizon and, therefore, between the effective interior evolution and the fundamental exterior evolution.

By following the ER=EPR approach originally developed by Susskind and Maldacena [52], the action of the surface of the apparent horizon as an entanglement island between the information contained in the interior and the modes outside the apparent horizon can be associated with an opportune entanglement entropy determined by the energetic content of sub-Planckian black holes of the variable energy density at the generalized Compton wavelength on the basis of relation:

$$S_A = \frac{N_k \Delta\rho_{qvE}{}^2 V^3}{k_B \eta c^2} \frac{\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE} V}\right)^2 + \left(\beta l_P^2 \frac{\Delta\rho_{qvE} V}{\hbar c}\right)^2\right]}{4G} \quad (34)$$

where k_B is the Boltzmann constant, N_k is the number of the virtual particles of the vacuum in the volume V and the parameter η plays the role of an inverse temperature, that can be related with the texture of sub-Planckian black holes. The effect of the entanglement entropy (34) of the texture of sub-Planckian black holes is of determining a connection between the information contained in the interior and the modes outside the apparent horizon, in the sense that one deals here with a quantum superposition of the form

$$\psi(\eta) = \sum_k e^{-\frac{\eta N_k \Delta\rho_{qvE} V}{c^2 \quad k_B}} |\psi_k\rangle \otimes |\psi_k\rangle \quad (35)$$

where $|\psi_k\rangle$ is the k-th energy eigenstate for a single mode outside the apparent horizon that can be associated with the wave functions (21)

satisfying the WDW equation (11). In other words, we can say that the fluctuations of the variable energy density at the generalized Compton wavelength determine the generation of a sort of quantum wormholes described by an entanglement entropy that is responsible of the connection between the information contained in the interior and the modes outside the apparent horizon and, therefore, between causally disconnected regions of the universe and their corresponding evolutions. The entanglement entropy which encodes the action of the surface of the apparent horizon as entanglement island between the information contained in the effective interior of the black hole and the modes outside the apparent horizon, introduces new perspective of explanation of the black hole information paradox. In fact, we can consider the possibility that the Hawking radiation, during its formation, becomes entangled with the region from the apparent horizon to the photon sphere rim, as a consequence just of the action of the surface of the apparent horizon as entanglement island, thus avoiding information loss during evaporation of the black hole. In other words, the entanglement entropy implies the generation of an entanglement between the forming Hawking radiation and the region between the apparent horizon and the photon sphere rim and, therefore, there is no information loss during evaporation of the black hole. And this action of the entanglement entropy in determining a connection between the Hawking radiation and the region between the apparent horizon and the photon sphere rim is transmitted by quantum wormholes which transmit the information between interior and exterior of the black hole. This means that the entanglement entropy of the apparent horizon allows a promising solution of the information paradox that avoids the violation of quantum mechanics' principle of unitarity.

The entanglement action of the surface of the apparent horizon corresponds to a deformation of the geometry described by the metric

$$ds^2 = -c^2\left(1-\frac{2G\Delta\rho_{qvE}Vr^2}{c^4\left(r^2+\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}}\right)dt^2 + \frac{dr^2}{1-\frac{2G\Delta\rho_{qvE}Vr^2}{c^4\left(r^2+\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}}} + r^2d\Omega^2 \quad (36)$$

where $d\Omega = \mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2$. The metric (36) means that the entanglement action of the surface of the apparent horizon is associated to the actualization of wormholes that embed non-local

correlations, and therefore cause the generation of entangled states of disconnected regions of the universe in a similar way to the action of an ER bridge. In this way, one obtains in this approach a sort of generalization of the ER=EPR conjecture, in that the wormhole formation transmitting the information between the interior and the exterior of a black hole (i.e. above the photon sphere rim) corresponds to the dissipative features of fluctuations of the texture of sub-Planckian black holes at the generalized Compton wavelength. This means that texture of the sub-Planckian black holes are the real ultimate origin of the peculiar masses that can generate, through a gravitational collapse, a black hole till the apparent horizon. On the basis of the entanglement entropy (34), the metric (36) gives rise to the Bekenstein-Hawking entropy

$$S_A = \frac{N_k \Delta\rho_{qvE}{}^2 V^3}{k_B \eta c^2} \frac{\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]}{4G} \cdot \left(1 - \frac{8\pi\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]}{A}\right) \sqrt{1 + \frac{4\pi\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]}{A}} + \frac{3\pi N_k \Delta\rho_{qvE}{}^2 V^3}{k_B \eta c^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right] \cdot \ln\left(\frac{1}{2l_0}\left(\sqrt{\frac{A}{\pi}} + \sqrt{\frac{A + 4\pi\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^2}{\pi}}\right)\right) \quad (37).$$

where A is the area of the wormhole metric, that plays the role of the cut through the ER bridge and is fixed by the generalized Compton wavelength. Now, by defining $A = 8\pi\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]$, one obtains the following quantum-modified Bekenstein entropy associated with the sub-planckian black holes of the variable energy density acting as quantum wormholes:

$$S_A = \frac{3\pi N_k \Delta\rho_{qvE}{}^2 V^3}{k_B \eta c^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right] \ln\left(\sqrt{2} + \sqrt{3}\right) \quad (38).$$

Therefore, we can say that the entanglement entropy (34) which encodes the action of the surface of the apparent horizon as entanglement island by generating an entanglement between the forming Hawking radiation and the region between the apparent

horizon and the photon sphere rim, therefore avoiding the information loss during evaporation of the black hole, determines a deformation of the metric that corresponds to the actualization of sub-planckian black holes acting as quantum wormholes, that are characterized by the quantum-modified Bekenstein entropy (38). The modified Bekenstein entropy (38) is in agreement with the treatment provided in [53] close to the zero-point (Planck) length. Moreover, the metric (36) and the corresponding quantum-corrected Bekenstein entropy (38) imply that the apparent horizon acting as entanglement channel between interior information and exterior information can be described by the characteristic length

$$r = \sqrt{2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right] \quad (39)$$

and by the characteristic mass

$$M = 3\sqrt{3}\frac{\sqrt{\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]}}{4G} c^2 \quad (40).$$

Here, it is interesting to remark that, in the domain where the generalized Compton wavelength tends to the Planck length, the mass (40) leads to a numerical value of the mass that is close to the Planck mass.

If, as we have shown above, the entanglement entropy (34) of the surface of the apparent horizon, because of its action in generating an entanglement between the forming Hawking radiation and the region between the apparent horizon and the photon sphere rim, allows us to avoid information loss during evaporation of the black hole, in a similar way the sub-planckian black holes acting as quantum wormholes, described by the quantum-modified Bekenstein entropy (38), which transmit the information between the interior and the modes outside the apparent horizon, imply that there is no information loss after evaporation of the black hole. In the light of the non-local correlations embedded by the quantum wormholes that transmit the information between the interior and the modes outside the apparent horizon, some information about the interior might be detectable on the surface of the apparent horizon, where pairs of virtual particles jump in and out of existence in such a way that there is no paradox if one of these quantum entangled pairs is split up by the apparent horizon and is held in the black hole, while the other flies out as Hawking radiation. In this approach, there is therefore no paradox regarding the fate of the information contained in the black hole after its evaporation, in other words the information paradox is easily resolved also under these constraints.

The entanglement action of the surface of the apparent horizon can provide a new key of reading, at a deeper level, of the results recently obtained by Bousso and Penington, regarding the existence of entanglement surfaces that exist slightly outside the event horizon and that, for a supermassive black hole, could extend as much as an atom's length [54]. In fact, Bousso's and Penington's entanglement surfaces outside the event horizon and extending as an atom's length, can be seen as a result, as an emergent fact, from the more fundamental entanglement action of the surface of the apparent horizon described by the entanglement entropy (34) and the subsequent formation of quantum wormholes, that are characterized by the quantum-modified Bekenstein entropy (38) and transmit the information between the interior of the horizon and the modes outside the horizon. In other words, we consider the possibility that the entanglement islands outside the event horizon invoked by Bousso and Penington are indeed a macroscopic effect of a more fundamental, primordial action of entanglement provided by the surface of the apparent horizon that is described by the entanglement entropy (34), that produces a deformation of the geometry expressed by the metric (36) which in turn corresponds to the actualization of sub-planckian black holes acting as quantum wormholes which are described by the modified Bekenstein entropy (38), where all these processes are ultimately ruled by the dissipative features of the vacuum at the generalized Compton wavelength. Moreover, we underline that the entanglement action of the surface of the apparent horizon and the resulting n on-local action of the quantum wormholes that transmit the information between the effective interior and the modes in the exterior by means of the entanglement entropy (34) and the modified Bekenstein entropy (38) respectively, is compatible with the holographic approach – proposed in [55] – where, after the formation of a black hole from collapse, the information in the black hole interior remains encoded in the boundary, in such a way that the area of the black hole's apparent horizon is precisely the maximum holographic entanglement entropy that reproduces the geometry of the exterior.

6. About the relation between interior evolution and exterior evolution: the perspective effect

The mathematical formalism developed in section 5 shows that the interior spacetime of the black hole emerges as an effective description of a given exterior time. In this regard, on the basis of the treatment provided in [56], the interior of a black hole provides a way of reorganizing the degrees of freedom associated to the transitory

phenomenon of an infalling object dissolving into the (apparent) horizon. Here, the interior of the black hole can be seen as an inner boundary of spacetime, which holographically encodes the information inside, thus implying that the modes outside the horizon contain any information of the effective interior which therefore exists in the causal past of the Hawking radiation. As a consequence, the interior spacetime emerges as an effective description described by an effective theory containing a zone $r_S < r < r_Z$, where r_S is the location of the horizon in the Schwarzschild radial coordinate r, r_Z is the location of the outer edge of the near black-hole region inside the barrier of the effective gravitational potential generated by the black hole, up to a time

$$T_{t_x} = t_x + 2\frac{r_+}{c}\ln\frac{r_+}{l_p} \quad (41)$$

where r_+ is the radius of the apparent horizon of the black hole corresponding to the time $t_x < T_{evap}$.

Now, in the model of the 3D DQV, the treatment based on equation (41) suggested in [57] can receive a new re-reading that leads directly to a compelling solution of the problems connected to Hawking radiation, interior time evolution and exterior time evolution. In our model, because of the origin of the intrinsic periodicity of the sub-Planckian black holes of the 3D DQV from the dissipative features of the 3D DQV at the generalized Compton wavelength and the consequent processes of entanglement between interior information and exterior information of a black hole, that are determined by the apparent horizon and the resulting sub-planckian black holes acting as quantum wormholes, respectively encoded by the entanglement entropy (34) and the modified-Bekenstein entropy (38), the physics characterizing the black hole interior can be associated to a perspective effect ultimately fixed by the variable energy density of the 3D DQV, i.e. to an effective theory regarding a spacetime region K_{t_x} containing a portion of the zone $\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2} < r < r_Z$ where r_Z is the location of the outer edge of the near black-hole region inside the barrier of the effective gravitational potential generated by the black hole, only up to a time

$$T_{t_x} = t_x + 2\frac{r_+}{c}\ln\frac{r_+\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2}\;\frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]^2}}}{c} \quad (42).$$

The time (42) is directly fixed by a corresponding behaviour of the variable energy density of the 3D DQV, in the sense that, in equation (42), r_+ is the radius of the apparent horizon of the black hole corresponding to the time t_x given by relation

$$t_x = \frac{\hbar\eta}{S_A} \quad (43)$$

where S_A is the modified Bekenstein entropy given by (38) and therefore

$$t_x = \frac{\hbar k_B \eta^2 c^2}{3\pi N_k \Delta\rho_{qvE}{}^2 V^3 \left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right] \ln(\sqrt{2}+\sqrt{3})} \quad (44).$$

In other words, we can say that the time instants defined by (42) and (44) have the physical meaning of numerical orders of the opportune fluctuations of the quantum vacuum energy density, that are associated to opportune networks of sub-planckian black holes of the variable energy density.

On the basis of equations (42)-(44), the physics characterizing the interior portion of K_{t_x} of the black hole describes correlations between the degrees of freedom, that correspond to the time interval

$$t_x < t < T_{t_x} \quad (45)$$

and, therefore, can be interpreted as originating from the infalling time evolution generated by an opportune operator without involving a further exterior time evolution, because of the action of the dissipative features of the 3D DQV at the generalized Compton wavelength, that lead to the action of the apparent horizon as entanglement island and the consequent quantum wormholes, respectively described by the entanglement entropy (34) and the quantum-modified Bekenstein entropy (38), therefore generating the entanglement between interior information and exterior information. Therefore, in the model of the 3D DQV whose elementary constituents are sub-Planckian black holes characterized by dissipative features at the generalized Compton wavelength and that lead to collapsing dust shells described by the wave function (21) and by the maximum density (27), there is no paradox as regards the link between the interior time evolution to the black hole and the exterior time evolution. There is no contradiction between interior description and exterior description. The connection between the interior and the exterior time evolution of the black hole appears as a direct natural consequence of the rearrangement of correlations determined by the action of the surface of the apparent horizon as an entanglement island and transmitted by the non-local action of the resulting sub-planckian black holes acting as quantum wormholes. In other words, we can say that the connection between

the interior and the exterior time evolution of the black hole can be seen as a sort of perspective effect, which is caused by this rearrangement of correlations determined by apparent horizon and corresponding quantum wormholes.

The occurrence of an event x in the interior background is related with exterior modes between $t_{min} = min\{t_x : x \in K_{t_x}\}$ and $T_{t_{max}}$ where $t_{max} = max\{t_x : x \in K_{t_x}\}$ and, for any point in the interior description, $T_{t_{max}} < T_{evap}$ where T_{evap} is the time corresponding to the evaporation of the black hole. This means that, in the exterior description, by virtue of the perspective effect determined by the dissipative features of the vacuum and ultimately derived from the entanglement interaction between interior and exterior produced by the surface of the apparent horizon and transmitted by the non-local action of the quantum wormholes, the physics experienced by an interior observer at a given point x already occurred before the evaporation of the black hole. Thus, whatever are the constraint conditions of the Hawking radiation, the detector cannot influence the actual experience of the interior observer inside the black hole and this occurs ultimately as a result of the dissipative features of the 3D DQV corresponding to opportune fluctuations of the quantum vacuum energy density.

By following [56], one can also extend the analysis to the case in which one deals with operators before the complete evaporation of the black hole, by considering an infalling observer who reaches the apparent horizon at some exterior time t_f. If the effective theory of the interior corresponding to the time t_f describes the experience of the observer shortly after crossing the horizon, this does not necessarily imply that the effective theory describes well all the experiences of this observer. For example, the observer may accelerate towards the horizon, eventually leaving the region K_{t_f} encoding the rearrangement of correlations associated with the entanglement which connects the information contained in the effective interior of the black hole and the modes outside the apparent horizon. In this case, the experience of the infalling observer corresponds to the time

$$t_{comp} = t_f + t_{scr} \quad (46)$$

in the exterior description, where

$$t_{scr} = 4\frac{r_+}{c}\ln\frac{r_+}{c\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2}\;\frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]^2}}} \quad (47)$$

is the scrambling time, which depends logarithmically of the radius r_+ of the apparent horizon of the black hole corresponding to the time t_x as

well as of the intrinsic periodicity of the sub-planckian black holes. On the basis of equation (47), the scrambling time is directly fixed by the behaviour of the variable energy density of the 3D DQV and can be interpreted here as the minimum time needed for quantum information to be extracted by outside observers from the black hole after the apparent horizon has absorbed an infalling observer. The experience of the infalling observer can be associated to the time (44) in the sense that the effective theory leads to a late trajectory of the observer that can be associated with the time

$$t_f^{'} = t_f + 2\frac{r_+}{c}\ln\frac{r_+\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2}\quad\frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE^V}}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE^V}}{\hbar c}\right)^2\right]^2}}}{c} \quad (48)$$

even in the worst case of motion of the observer outward at the speed of light crossing the apparent horizon. By following the same route that led to equation (45), any experience of the observer in the interior corresponds to the time

$$T_{t_f^{'}} = t_f + t_{scr} \quad (49).$$

On the other hand, if one uses the general argument provided in [6], one can say that the information about an object that fell into the black hole at t_f emerges in Hawking radiation only after the time $t_f + t_{scr}$ as a consequence of the perspective effect, of the rearrangement of correlations determined by the action of the surface of the apparent horizon as entanglement island between interior and exterior of the black hole. Therefore, as a consequence of the action of the scrambling time intended as a numerical order of material change associated with the dissipative features of the vacuum at the generalized Compton wavelength as well as of the radius of the apparent horizon, it follows that any operation on Hawking radiation — even if it is performed before the time of evaporation — cannot influence the experience of an observer in the interior [57, 58].

The treatment made in this chapter leads to the following interpretation of the black hole's singularity [59]. From an exterior perspective, the immediate thermalization of an object when it encounters the apparent horizon does not occur. Instead, a distinct excitation on the horizon takes place for some duration in the form of a perspective effect generated by the dissipative features of the vacuum at the generalized Compton wavelength. Over the scrambling time t_{scr}, where one deals with gradual dissipation of this excitation into the horizon, the effective description as an object traversing the near-empty interior of the black hole works. After the object's excitation is

fully integrated into the apparent horizon, the perspective effect associated with the rearrangement of correlations determined by the dissipation processes of the vacuum and the corresponding effective theory that describes the connection between the information contained in the effective interior of the black hole and the modes outside the apparent horizon, do not hold anymore. Interior description and exterior description emerge therefore as complementary aspects, that are indeed not contradictory because of the appearance of this fundamental perspective effect of the rearrangement of correlations determined by the entanglement action of the surface of the apparent horizon and the non-local action of the resulting quantum wormholes, that ultimately are originated by the dissipative features of the vacuum at the generalized Compton wavelength.

Since the features of the black hole evolution involve collapsing dust shells which terminate at the apparent horizon as a consequence of the dissipative features of the 3D DQV at the generalized Compton wavelength, an exterior observer cannot recover information about an object which traversed the apparent horizon at an earlier time. Thus, in this picture, there is no problem of cloning if the observer jumps into the horizon. In other words, an observer cannot obtain a second copy of the information and the no-cloning theorem is naturally saved as a consequence of the entanglement action of the surface of the apparent horizon between the information contained in the effective interior of the black hole and the modes outside the apparent horizon. In particular, by substituting the scrambling time (47) inside the generalized energy-time uncertainty relation

$$\Delta E \Delta t \geq \frac{\hbar}{2}\left(1+\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (50),$$

the duplication of quantum information is avoided (and therefore the information cloning is evaded) if one deals with a scale of energy

$$\Delta E \gg \frac{\hbar c}{8 r_+ \ln \frac{r_+}{c}\sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}-\frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^2}}} \cdot \left(1+\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (51).$$

We underline here that the result (48) turns out to be compatible with the treatment in [60], if the mass of the black hole satisfies relation

$$Mc = \frac{\hbar}{8r_+ \ln \frac{r_+ \sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^2}}}{c}} \cdot \left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (52).$$

In summary, on the basis of equations (45) and (52), we can conclude that the cloning of information is avoided if one deals with a scale of energy that exceeds the quantity

$$\frac{\hbar c}{8r_+ \ln \frac{r_+ \sqrt{\frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^2}}}{c}} \left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right)$$

and this occurs when the scrambling time (47) is sufficiently large.

On the other hand, if we explore further the comparison with the Susskind and Maldacena ER=EPR approach, where virtual wormholes determine a connection between the black hole could and Hawking radiation [52], in our approach of 3D DQV ruled by the generalized Compton wavelength, as we have already underlined, the firewall is not present. The intrinsic periodicity of the sub-Planckian black holes of the variable energy density emerging from the dissipative features of the vacuum at the generalized Compton wavelength implies that the interior of a black hole can be considered as a way of reorganizing the degrees of freedom involved in the temporary phenomenon of an infalling object dissipating into the apparent horizon through the entanglement action of the apparent horizon characterized by the entanglement entropy (34) and the non-local action of the quantum wormholes associated with the fluctuations of the texture of the sub-Planckian black holes, described by the modified Bekenstein entropy (38). As a consequence of the entanglement action of the surface of the apparent horizon in generating the connection between the information contained in the effective interior of the black hole and the modes outside the apparent horizon, no operation performed on Hawking radiation can influence the experience of an infalling observer. Finally, we emphasize that, in the processes of gravitational collapse of dust shells determined by the dissipative features of the 3D DQV, the transition to extremely compact quantum objects, ruled by quantum gravity, giving rise to an apparent horizon whose surface acts as an entanglement island between the information inside the black hole and the modes outside the apparent horizon, can be associated (and are compatible) with the creation of baby-universes which will separate

from a plasma of large parent universes. As a consequence of the dissipative features of the vacuum acting at the generalized Compton wavelength, we can say that there is, on one hand, the evaporation of the observable part of the black hole at the time (47) and, on the other hand, a true entanglement between thermal radiation in our universe and a new universe beyond it (which is in the form of an island inside the black hole). These two universes together continue to be indeed in a pure quantum state, but separately they seem to be in a mixed state, thus leading to the result that, in the model of sub-planckian black holes of the variable energy density that are characterized by an intrinsic periodicity that is fixed by the dissipative features of the vacuum at the generalized Compton wavelength, there is no paradox associated to the evaporation of a black hole and there is no problem as regards unitarity of quantum mechanics, that turns out to be saved. As a consequence of the role of entanglement island by the surface of the apparent horizon, the black hole evaporation leads to the result that every black hole in a given universe can be seen as a white-hole source of a new universe, thus providing a model of multiverse where each decoupling bag of gold = black hole for us and a white-hole for some emerging new universe has all the quantum numbers (charges), associated with gauge symmetries, that are vanishing, but can have non-trivial entanglement with the parent universe and also non-trivial values of ungauged charges, like baryon number, thus determining new options to resolve the baryon asymmetry problem [61]. In this way, in the cosmological background determined by the dissipative features of the vacuum, our universe – as well as other baby universes – can be considered as white holes emerging from a black hole in a plasma of large parent universes. Each black hole is surrounded by Hawking radiation, which stays in its own universe, while the other content of the black hole decouples from it at around the Page time (intended as the last numerical order of material change associated with the decoupling of the interior of the black hole) and gives birth to a new baby universe, whose origin, inside the new universe, can be associated to a white hole. Moreover, if one assumes that the end of the black hole evaporation is associated to a mild singularity, the black hole interior can be seen as a closed universe that is separated from the ambient space describing the exterior of the black hole, compatibly with the interpretation provided in [62], according to which, after the black hole evaporates, its microscopic information is encoded in the states of the baby universes arising in the system of replicated black holes associated with the plasma of large parent universes.

5. Conclusions

The approach of 3D DQV whose elementary constituents are sub-planckian black holes of the variable energy density that are characterized by an intrinsic periodicity that is fixed by the dissipative features of the vacuum at the generalized Compton wavelength, leads to relevant perspectives of handling the firewall and information paradoxes connected to black holes.

Before all, as regards the issue of the complementarity of the black holes, the three fundamental assumptions invoked by AMPS in [7, 8], i.e.:

1. Hawking radiation is pure;
2. effective field theory is valid outside a stretched horizon;
3. infalling observers encounter nothing unusual as they cross the horizon

are not necessarily incompatible, in the sense that, in our model, a lattice of collapsing dust shells, namely micro-universes described by the wave functions (21), as a consequence of their maximum density (27), condense to an apparent horizon which is characterized by the coarse-grained entropy (31) that is directly fixed by the dissipative features of the 3D DQV at the generalized Compton wavelength, thus implying that equivalence principle, Hawking radiation and quantum entanglement are not incompatible. Since the dissipative processes of the 3D DQV at the generalized Compton wavelength determine the formation of an apparent horizon, our model demonstrates in a direct way the impossibility of the formation of a firewall, allowing us to avoid the arguments involved in the AMPS work and resolve the firewall paradoxes of black holes.

Moreover, during the gravitational collapse of the black hole till the apparent horizon, because of the dissipative features of the 3D DQV at the generalized Compton wavelength, the surface of the apparent horizon gets the role of entanglement island between interior and exterior. The entanglement action of the apparent horizon is encoded by the entanglement entropy (34) and corresponds to a deformation of the geometry (36) that leads to the formation of the non-local action of quantum wormholes, characterized by the modified Bekenstein entropy (38), that create a connection between the information contained in the effective interior of the black hole and the modes outside the apparent horizon. As a consequence of the perspective effect caused by the rearrangement of correlations which are determined by the apparent horizon and the quantum wormholes, interior description and exterior description emerge as complementary aspects, that are not contradictory. The model based on the

entanglement action of the apparent horizon and the non-local action of the resulting quantum wormholes allows us to provide a compelling solution to the information paradox can both during evaporation of the black hole and after evaporation of the black hole. In fact, on one hand, the entanglement entropy of the surface of the apparent horizon implies the generation of an entanglement between the forming Hawking radiation and the region between the apparent horizon and the photon sphere rim, which is transmitted by non-local quantum wormholes, implying that there is no information loss during evaporation of the black hole. On the other hand, the sub-planckian black holes acting as quantum wormholes, described by the quantum-modified Bekenstein entropy (38), which transmit the information between the interior and the modes outside the apparent horizon, imply that there is no information loss after evaporation of the black hole. In this way, the action of the surface of the apparent horizon described by the entanglement entropy (34) and the generation of quantum wormholes characterized by the modified Bekenstein entropy (38) allow a promising solution of the information paradox that avoids the violation of quantum mechanics' principle of unitarity.

In this picture, the evolution of the system after the formation of the apparent horizon can be seen as a perspective entanglement effect owed to the dissipative features of the vacuum at the generalized Compton wavelength, where correlations between the degrees of freedom associated with the time interval (45) are rearranged in such a way that they can be interpreted as originating from the infalling time evolution generated by an opportune operator without involving a further exterior time evolution. Moreover, the evolution of the collapsing dust shells which terminate at the apparent horizon as a consequence of the dissipative features of the 3D DQV at the generalized Compton wavelength, has also the merit to naturally save the no-cloning theorem.

The attempt to handle the firewall and information paradoxes in the model explored in this paper turns out to be compatible also with the idea of a multiverse. In fact, the processes of gravitational collapse can be associated to the creation of baby-universes which will separate from a plasma of large parent universes where, as a consequence of the dissipative features of the vacuum acting at the generalized Compton wavelength, on one hand, one has the evaporation of the observable part of the black hole and, on the other hand, one has a true entanglement between thermal radiation in our universe and a new universe. The two universes together continue to be indeed in a pure quantum state, but separately they seem to be in a mixed state and

therefore there is no paradox associated to the evaporation of a black hole and there is no problem as regards unitarity of quantum mechanics, that turns out to be saved.

In summary, despite at its germinal stages, we can say that our model of sub-planckian black holes of the variable energy density of the three-dimensional dynamical quantum vacuum suggests a compelling attempt to treat problems and paradoxes connected to black holes.

Finally, our model provides a novel key of re-reading of the non-existence of a central singularity, which is alternative with respect to current approaches, in particular those involving the insertion of an imaginary time through the so-called Wick rotation, which provide ad hoc mechanisms leading to ad hoc solutions [63, 64]. The results obtained in this paper – and, in particular, the perspective effect determined by the action of the surface of the apparent horizon as entanglement island between interior information and exterior information – seem to be compatible with a recent proposal of solution of the problem of singularities of Lorentz-Euclidean black holes, named "atemporality", involving a dynamical mechanism by which an observer pointing towards the event horizon cannot reach the singularity in r=0, in a Lorentz-Euclidean-Schwarzschild metric, because both the time variable and radial velocity become imaginary inside the black hole [65]. In the "atemporality" approach, any massive particle stops at the event horizon because, if entering it, conservation laws would be violated as a consequence of the appearance of an imaginary radial velocity. The possible links between the "atemporality" approach and the model of sub-planckian black holes of the variable energy density of the 3D DQV introduce new scenarios which are all to be explored.

References

[1] X. Dai, "The black holes paradoxes and possible solutions", *Journal of Physics: Conference Series* **1634**, 012088 (2020).

[2] L. Susskind, L. Thorlacius and J. Uglum, "The Stretched horizon and black hole complementarity", *Physical Review D* **48**, 3743 (1993).

[3] L. Susskind, "String theory and the principles of black hole complementarity", *Physical Review Letters* **71**, 2367 (1993).

[4] L. Susskind and L. Thorlacius, "Gedanken experiments involving black holes", *Physical Review D* **49**, 966 (1994).

[5] D.N. Page, "Information in black hole radiation", *Physical Review Letters* **71**, 3743 (1993).
[6] P. Hayden and J. Preskill, "Black holes as mirrors: Quantum information in random subsystems", *Journal of High Energy Physics* **09**, 120 (2007).
[7] A. Almheiri, D. Marolf, J. Polchinski and J. Sully, "Black holes: complementarity or firewalls?", *Journal of High Energy Physics* **62** (2013).
[8] A. Almheiri, D. Marolf, J. Polchinski, D. Stanford and J. Sully, "An Apologia for Firewalls", *Journal of High Energy Physics* **09**, 018 (2013).
[9] S.L. Braunstein, S. Pirandola and K. Zyczkowski, "Better Late than Never: Information Retrieval from Black Holes", *Physical Review Letters* **110**, 101301 (2013).
[10] S.W. Hawking, "Information preservation and weather forecasting for black holes", arXiv:1401.5761 (2014).
[11] C. Vaz, "Black holes as gravitational atoms", *International Journal of Modern Physics D* **23**, 1441002 (2014).
[12] J.E. Jacak, "Topology-induced quantum transition in multi-particle systems in vicinity of a black hole", *Classical and Quantum Gravity* **41**, 035006 (2024).
[13] J.E. Jacak, "Modification of premises for the black hole information paradox caused by topological constraints in the event horizon vicinity", *Entropy* **26**, 1035 (2024).
[14] S.W. Hawking, "Black hole explosions?", *Nature* **248**, 30–31 (1974).
[15] A. Bekenstein, "Black holes and the second law", *Lettere Al Nuovo Cimento* **4**, 737–740 (1972).
[16] R.J. Adler and D.I. Santiago, "On gravity and the uncertainty principle", *Modern Physics Letters A* **14**, 1371 (1999).
[17] F. Scardigli, "Generalized uncertainty principle in quantum gravity from micro-black hole gedanken experiment", *Physics Letters B* **452**, 39-44 (1999).
[18] B.J. Carr, "The Black Hole Uncertainty Principle Correspondence", *Springer Proceedings Physics* **170**, 159-167 (2016).
[19] M.J. Lake and B. Carr, "The Compton-Schwarzschild relations in higher dimensions", arXiv:1611.01913 [gr-qc] (2016).
[20] M.J. Lake and B. Carr, "Does Compton/Schwarzschild duality in higher dimensions exclude TeV quantum gravity?", *International Journal of Modern Physics D*, 1930001 (2018).
[21] M.J. Lake and B. Carr, "The Compton-Schwarzschild correspondence from extended de Broglie relations", *Journal of*

High Energy Physics **1511**, 105 (2015) doi:10.1007/JHEP11 (2015).

[22] B.J. Carr, J.R. Mureika and P. Nicolini, "Sub-Planckian black holes and the generalized uncertainty principle", *Journal of High Energy Physics* **2015**, 07052 (2015).

[23] J. Carr, L. Modesto and I. Prémont-Schwarz, "Generalized uncertainty principle and self-dual black holes", arXiv:1107.0708 [gr-qc] (2011).

[24] B.J. Carr, "The generalized uncertainty principle and higher dimensions: linking black holes and elementary particles", arXiv:2302.12609v1 [gr-qc] (2023).

[25] A.F. Ali, S. Das and E.C. Vagenas, "Discreteness of space from the generalized uncertainty principle", *Physics Letters B*, 678, 497-499 (2009).

[26] P. Chen, Y.C. Ong and D.-h. Yeom, "Generalized uncertainty principle: implications for black hole complementarity", *Journal of High Energy Physics* **12**, 021 (2014).

[27] F. Yang, "Generalized uncertainty principles models' multifaceted impact on black hole thermodynamics and entropy conservation during Hawking radiation", *Modern Physics Letters A*, https://doi.org/10.1142/S0217732325501329 (2025).

[28] D. Fiscaletti, The timeless approach. Frontier perspectives in 21st century physics, World Scientific, Singapore (2015).

[29] D. Fiscaletti, "About dark energy and dark matter in a three-dimensional quantum vacuum model", *Foundations of Physics* **46**, 10, 1307-1340 (2016).

[30] D. Fiscaletti and A. Sorli, "About a three-dimensional quantum vacuum as the ultimate origin of gravity, electromagnetic field, dark energy ... and quantum behaviour", *Ukrainian Journal of Physics* **61**, 5, 413-431 (2016).

[31] D. Fiscaletti and A. Sorli, "Dynamical quantum vacuum and relativity", *Annales UMCS Sectio AAA: Physica* **LXXI**, pp. 11-52 (2016).

[32] D. Fiscaletti and A. Sorli, "Quantum vacuum energy density and unifying perspectives between gravity and quantum behaviour of matter", *Annales de la Fondation Louis de Broglie* **42**, 2, 251-297 (2017).

[33] D. Fiscaletti and A. Sorli, "Quantum relativity: variable energy density of quantum vacuum as the origin of mass, gravity and the quantum behaviour", *Ukrainian Journal of Physics* **63**, 7, 623-644 (2018).

[34] D. Fiscaletti, "About dark matter as an emerging entity from elementary energy density fluctuations of a three-dimensional quantum vacuum", *Journal of Theoretical and Applied Physics* **14**, 203-222 (2020).

[35] D. Fiscaletti and A. Sorli, "Generalized uncertainty relations, particles, black holes, and Casimir effect in the three-dimensional quantum vacuum", *Theoretical and Mathematical Physics* **214**, 1, 132-151 (2023).

[36] D. Fiscaletti, "Generalized uncertainty relations, generalized Compton wavelength and particles in a quantum foam described by a variable energy density", *Hadronic Journal* **47**, 183-206 (2024).

[37] F. Scardigli and R. Casadio, "Gravitational tests of the generalized uncertainty principle", *European Physical Journal C* **75**, 425 (2015).

[38] D. Fiscaletti, "Implications of generalized Compton wavelength in the effects of general relativity", *Theoretical and Mathematical Physics*, accepted for publication, 2024.

[39] R.C. Pantig, A. Övgün and G. Lambiase, "Thenomenology of Schwarzschild-like black holes with a generalized Compton wavelength", arXiv:2504.18226v1 [gr-qc] (2025).

[40] D. Fiscaletti, "About the multiverse in the three-dimensional quantum vacuum with variable energy density", *Bulgarian Journal of Physics* **51**, 2, 185-210 (2024).

[41] D. Dolce, "Introduction to the quantum theory of elementary cycles: the emergence of space, time and quantum", in *Beyond Peaceful Coexistence: The Emergence of Space, Time and Quantum*, eds I. Licata and G. 't Hooft, World Scientific (2016), pp. 93-135.

[42] D. Dolce, "New stringy physics beyond quantum mechanics from the Feynman path integral", DOI:10.21203/rs.3.rs-503118/v1 (2022).

[43] D. Fiscaletti and A. Sorli, "Perspectives about scales and hierarchies in a three-dimensional quantum vacuum ruled by generalized uncertainty relations", *Bulgarian Journal of Physics* **50**, 4, 412-438 (2023).

[44] C. Corda, "Black hole spectra from Vaz's quantum gravitational collapse", arXiv:2305.02184v2 [gr-qc] (2023).

[45] Y. Nomura and S.J. Weinberg, "Entropy of a vacuum: what does the covariant entropy count?", *Physical Review D* **90**, 104003 (2014).

[46] N. Engelhardt and A.C. Wall, "Decoding the apparent horizon: a coarse-grained holographic entropy", arXiv:1706.02038v4 [hep-th] (2019).

[47] R. Penrose, "Gravitational collapse and space-time singularities", *Physical Review Letters* **14**, 3, 57 (1965).

[48] R.P. Kerr, "Do black holes have singularities?", arXiv:2312.00841.pdf (2023).

[49] R.P. Kerr, "Gravitational of a spinning mass as an example of algebraically special metrics", *Physical Review Letters* **11**, 237 (1963).

[50] L.D. Landau and E.M. Lifshitz, *The classical theory of fields*, Pergamon Press LTd., Oxford, UK (1971).

[51] I. Licata and D. Fiscaletti, "Holography and nucleation processes from the primeval Wheeler-DeWitt equation in a de Sitter universe", *International Journal of Theoretical Physics* **63**, 122 (2024).

[52] J. Maldacena and L. Susskind, "Cool Horizons for entangled black holes", *Fortschritte der Physik* **61**, 9, 781-811 (2013).

[53] K. Jusufi, E. Moulay, J. Mureika and A.F. Ali, "Einstein-Rosen bridge from the minimal length", *European Physical Journal C* **83**, 282 (2023).

[54] R. Bousso and G. Penington, "Islands far outside the horizon", arXiv:2312.03078v3 [hep-th] (2023).

[55] N. Engelhardt and A.C. Wall, "Decoding the apparent horizon: a coarse-grained holographic entropy", arXiv:1706.02038v4 [hep-th] (2019).

[56] B. Concepcion, Y. Nomura, K. Ritchie and S. Weiss, "Complementarity for a dynamical black hole", *Physical Review D* **110**, 086002 (2024).

[57] W.G. Unruh and R.M. Wald, "Acceleration radiation and generalized second law of thermodynamicals", *Physical Review D* **25**, 942 (1982).

[58] A.R. Brown, "Tensile strength and the mining of black holes", *Physical Review Letters* **111**, 211301 (2013).

[59] Y. Nomura, "Reanalyzing an evaporating black hole", *Physical Review D* **99**, 086004 (2019).

[60] W. Kim and M. Nam, "Investigation of black hole complementarity in ADS_2 black holes", arXiv:2310.13274v2 [hep-th] (2024).

[61] A. Morozov, "On information paradox and the fate of black holes", arXiv:2304.00197v1 [hep-th] (2023).

[62] D. Marolf and H. Maxfield, "Observations of Hawking radiation: The Page curve and baby universes", *Journal of High Energy Physics* **04**, 272 (2021).

[63] A. Zee, *Quantum Field Theory in a Nutshell*, 2nd edn. Princeton University Press, Princeton (2010).

[64] J.B. Hartle, S.W. Hawking and T. Hertog, "The Classical Universes of the No-Boundary Quantum State", *Physical Review D* **77**, 123537 (2008).

[65] S. Capozziello, S. De Bianchi and E. Battista, "Avoiding singularities in Lorentzian-Euclidean black holes: The role of atemporality", *Physical Review D* **109**, 10, 104060 (2024).